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FIELD EVALUATION OF OCEAN WAVE MEASUREMENTS WITH GPS BUOYS
by
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September 2010
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FIELD EVALUATION OF OCEAN WAVE MEASUREMENTS WITH GPS BUOYS

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LIST OF ACRONYMS AND ABBREVIATIONS

2D RMS:	Twice the Distance Root Mean Square
Θm:	Dominant Wave Direction
ADCP:	Acoustic Doppler Current Profilers
DGPS:	Differential Global Positioning System
EGNOS:	European Geostationary Navigation Overlay Service
GPS:	Global Positioning System
HF:	High Frequency
Hs:	Significant Wave Height
NDBC:	National Data Buoy Center
ONR:	Office of Naval Research
RF:	Radio Frequency
SD:	Secure Digital
Tp:	Dominant Wave Period
UTC:	Coordinated Universal Time
WAAS:	Wide Area Augmentation System
WaMoS II:	Wave Monitoring System

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I. INTRODUCTION

Ocean waves are capable of massive destruction and endless beauty. Unraveling the mysteries of their generation and predicting their height has been a pursuit of sea fairing people and coastal dwellers throughout history. There are many different kinds of open water waves; among them are wind waves, tides and tsunamis. Here we will be concerned with wind waves, driven by wind blowing over the sea surface (Lighthill 1962). The friction in the atmospheric boundary layer causes pressure perturbations that displace the sea surface. The earth's gravitational force acts as a restoring force, causing oscillations that are called surface gravity waves. These waves are created and limited by the strength of the wind that is blowing over the water's surface, the time this wind is in contact with the water's surface, and the distance of open water also known as fetch over which the waves grow under the influence of the wind. When wind waves leave their source area, they decouple from the atmospheric influence and become what is known as swell waves. Swell waves can travel vast distances across the open ocean with little loss of energy. In coastal areas, waves interact with subsurface bathymetry and dissipate in shallow water and in the surf zone. Predicting wave properties is therefore a problem of immense complexity and an area of active research.

A. MOTIVATION

Accurate forecasts of wave conditions are of the utmost importance to all who live, work, or travel on or near our oceans. A simple example of the necessity for wave prediction is the challenge of coastal engineering. The shoreline of every coastal state in the United States is covered with high-rise hotels and condominiums, not to mention parks and other more necessary infrastructure. These are all subject to whims of the sea. During storms, beaches are eroded and these structures come under assault by the crashing waves. A well-known example of this is the passage of nor'easters that often cause extensive damage on the barrier islands of the mid-Atlantic coast.

Understanding and predicting the natural phenomena of ocean surface waves is also of vital importance to the naval warfighter. The goal of the U.S. Naval

Meteorological and Oceanographic Command (METOC) is to possess the most accurate and timely knowledge of the environments in which we operate. The obvious focal point to the U.S. Navy lies at the cusp of the atmosphere and sea. The impact of this energetic environment on every dimension of Naval Operations has always and continues to be paramount in our planning and completion of the mission. The charge is to enable the naval command structure, using our wave prediction, to make the most practical, judicious, and effective decisions to complete their missions. The most obvious impact is amphibious operations where the navy is moving personnel as well as cargo ashore. Be it peaceful humanitarian assistance or wartime, the logistics of these maneuvers depend primarily on surf forecasting for their determination to conducting operations or not. During these actions too much is at stake to rely on anything less than the most precise forecast available.

Another essential operation where quantitative wave measurements are of the utmost importance is under-way replenishment (UNREP) also known as replenishment at sea. An UNREP involves the transfer of vital ships stores, fuel, and occasionally personnel from ship to ship while underway in the open oceans. There are two ways this transfer can be done, via the relief ship's helicopter landing on the receiving vessel's fantail to unload stores or by the meticulous maneuver of an alongside connection. The alongside UNREP involves the supply ship holding a steady course while the receiving ship pulls alongside and accepts cables that will transfer fluids and goods. These UNREP operations have set parameters that must be met to conduct such delicate maneuvers. Erroneous sea state measurements can certainly cause more than a simple nuisance to the operation.

B. WAVE PREDICTION

With the onset of high-performance supercomputers running global or regional wave prediction models such as Wave-Model (WAM) (Komen, 1994) and Wavewatch III (Tolman, 1996), we are now able to make considerably more accurate wave predictions than ever before. These models are driven by atmospheric models such as NOGAPS and

COAMPS and assimilate massive amounts of data gathered from ships observations, moored buoys, land-based meteorological stations, and satellites.

There are numerous sources of uncertainty in the model outcomes. The most obvious of these errors are found in the wind models and how they relate to the wave models. Capturing a wind field within a model is hard enough considering the variability of wind fields. The difficulty lies in determining intensity and detailed structure considering the observation platforms (Stoffelen, 1998). This error when embedded in a wave model can produce significant inaccuracy in wave forecasts. Wind fields for example are not exactly homogeneous. Observations of wind events over water are often taken from limited or single sources (ship observations and buoys) and are not indicative of the whole. Scatterometry collected from satellites has proven to be very useful in wind and wave modeling (Figa-Saldaña, 2002). The problem here arises in the grid spacing of scatterometer wind retrievals, which is considerably larger than the necessary detail needed to depict an accurate wave field for individual vessels.

Waves refract around shoaling areas and this can significantly affect the spatial distribution of wave energy (WMO, 1998). This creates another source of error in that bathymetry is not resolved (global models) or only coarsely resolved (regional models) in wave models. Grid spacing are often far too coarse to resolve island and coastlines causing degraded model performance in coastal areas. Including fine scale bathymetry in models covering large domains is often not feasible because of limited computational resources. Instead of relying on an inherently inaccurate model prediction, it is often advantageous to directly measure the waves in the area of interest using easy to deploy in-situ instruments such as surface-following buoys.

C. BUOYS

The oceans are vast and it would be enormously difficult and costly to maintain buoys throughout the seas. A more economical approach is to deploy buoys in carefully selected areas where direct wave measurements can enable the wave model to produce accurate forecasts for vessel traffic.

Open water wave buoys have been in development for some years. The National Data Buoy Center (NDBC) manages the development, operations, and maintenance a large national buoy network (NDBC, 2010). It operates as the National Oceanographic and Atmospheric Administration's (NOAA) center for all buoy data providing both meteorological and environmental information. Their first buoy was a 12-meter steel discus hull that measured surface pressure, temperature, wind speed and wind direction. These buoys were primarily positioned in the Gulf of Mexico and were expensive to built and maintain. The NDBC then created the 10-meter discus buoy that was capable of transmitting weather observation to shore to enable better forecasting of severe conditions. These buoys were also used to gather some wave data and eventually were built with aluminum hulls that were more cost efficient than the original steel buoys. Woods Hole Oceanographic office collaborated with NDBC to develop the 3-meter discus buoy. These buoys were aluminum-hulled and considerably easier to handle because they could be loaded on a flatbed truck and transferred to a desired location and deployed with relative ease compared to previous buoys. These buoys where widely used and sent to the Pacific, Atlantic, and the Gulf of Mexico. The 3-meter discus buoy uses the Hippy 40 heave-pitch-roll sensor manufactured by Datawell to measure sea surface displacement and wave slopes. A problem with these buoys was that they were not as hearty as the larger heavier buoys and could not sustain extreme sea states (Steele, 1992).

Another buoy that is widely used in buoy networks and for routine wave monitoring applications is the commercially available 0.9-meter diameter Directional Waverider (DWR) spherical buoy developed by Datawell of the Netherlands. The Waverider was an improvement over the 3-meter discus by using accelerometers to measure horizontal displacement in addition to the Hippy 40s heave, pitch, and roll sensors in a considerably smaller package (O'Reilly et al., 1996). The DWR was validated by Barstow and Kollstad in their 1991 report and by the end of the last century the NDBC's 3-meter discus buoy and Datawell DWR were the predominate in-situ wave measurement tools. Although they were both more economical than the earlier 12-meter and 10-meter buoys, they still required significant maintenance and were expensive (NDBC, 2010).

D. USE OF GPS TECHNOLOGY IN WAVE BUOYS

Recently GPS technology was introduced in wave buoys as a cheaper alternative to accelerometers and tilt sensors (Krogstad, 1999). GPS uses geostationary satellites and ground stations that send a coded signal to a receiver to determine precise location on the earth's surface. The system was originally created to be used by the U.S. military for navigation and land surveying. In 1983, President Ronald Reagan declassified GPS satellites to civilians and, since that time, the industry has expanded to become an integral part of our everyday life. Today we use GPS in everything from commercial construction, automobile and ship navigation, as well as recreational hiking and boating.

GPS technology has improved over the years through differential corrections know as DGPS. In their 2005 research Witte and Wilson noted that the "implementation of the Wide-Angle Augmentation System (WAAS), means that small, highly portable units are available offering the potential of superior accuracy in the determination of both position and speed" (Witte, 2005). The DGPS uses a network of ground stations that broadcast, over UHF, the difference between a fixed location on earth and the positions indicated by the GPS satellite. The WAAS described above covers North America while a similar system is used in Europe called the European Geostationary Navigation Overlay Service (EGNOS).

The concept of using GPS to accurately measure waves is certainly not new. Krogstad in his validation of buoys that used DGPS describes them as "more robust than the conventional accelerometer based wave sensor," due to the fact that the GPS receiver has no moving parts, is easier to deploy, and transport (Krogstad, 1999). Limited validation of Datawell's GPS-based buoys have demonstrated similar capabilities as the accelerometer-based buoys (Jeans, 2003). Although these newer GPS buoys are less expensive than the traditional accelerometer buoys, the costs are still prohibitive for large-scale navy applications. In this study, we examine the potential of using less expensive off-the-shelf GPS receivers in wave buoys. This project began when we mounted separate GPS units to our Datawell Waveriders for the purpose of gathering real time position information. This is necessary for tracking drifting buoys because the Datawell buoys updated buoy locations only every 30 minutes. This data is transmitted only for the purpose of locating and retrieving the buoy in the event it breaks free of its mooring, and does not allow for full Lagrangian monitoring. During a pilot project off the coast of southern California, we were surprised when we examined the GPS data to find how well the off-the-shelf GPS receivers tracked the orbital wave displacements. This finding motivated us to explore if an inexpensive GPS system can measure wave spectra accurately.

There are two different methods of deploying surface wave measuring buoys. Lagrangian measurements can be taken from drifting buoys flowing with the currents. This approach allows the buoy to experience the wave motion uninhibited and obtain simultaneous wave and current measurements. Of course, a drifting buoy can travel out of the area of operation, but if it is still gathering and/or transmitting data it can still be constructive. Alternatively, a moored buoy gathers measurements from a geographically fixed location. This can be a valuable means to gather continuous data for an area of interest. However it should be noted that a moored buoy provides neither a perfectly Lagrangian measurement nor a perfect Eulerian measurement and the moored response may somewhat degrade the quality of the data. As will be discussed in the next chapter, in our experiment we used both of these methods to collect wave measurements.

E. OTHER METHODS OF MEASURING WAVES

There are of course other ways to measure waves. Radar such as the Wave Monitoring System (WaMoS II), a commercially available system developed by Ocean SenseWare (Nieto, 1998) uses the existing marine X-Band radar on ships to measure the ambient ocean surface wave conditions. It analyses the temporal and spatial evolution of radar backscatter (Hessner, 2001) to infer wave and surface current estimates. Although the technology is promising, the radar transfer function is not well understood and an area of ongoing research. Validation of WaMoS with in-situ buoys is a primary objective of the High Resolution Air-Sea Interaction (HIRES) Departmental Research Initiative (DRI) funded by the Office of Naval Research (ONR) that also enabled the research in this paper.

Another method of monitoring waves is using underwater sensors mounted on the sea floor such as pressure sensors or current meters. Upward-looking Acoustic Doppler Current Profilers (ADCP) are also capable of gathering wave data by measuring the Doppler shift in sound scattered by small particles suspended in the water column that are advected by the wave motion. The drawback to bottom-mounted sensors is the fact that waves are attenuated over the water column, and thus they can only be used in shallow water, which is a significant limit to their effectiveness.

F. SCOPE

The Datawell Waveriders have been in commercial use for the last 30 years. In several field studies, the accelerometer-based wave measurements have been validated as one of the most reliable tools for recording sea state (O'Reilly et al., 1996). The main drawback of these buoys is the high cost. Even though the newer Datawell GPS buoys are smaller and lighter than earlier generation buoys, they are still too expensive for many applications that would require multiple or expendable buoys. In this study, we compare the Datawell accelerometer-equipped Waverider to the Datawell GPS buoys and off-the-shelf GPS technology to determine the viability of using a cheaper, smaller, and more easily deployable wave buoy. The validation study includes the first field test of a prototype drifting buoy developed at NPS using an off-the-shelf GPS receiver.

The wave data used in this study were collected during the HIRES 2010 experiment conducted off the coast of California near Bodega Bay, which will be discussed further in Chapter II. The cruise lasted from June 1 to July 1, 2010. Buoys for our study were deployed beginning June 5 with the final deployment on June 27. The cruise experienced multiple high wind events in which buoys were deployed as conditions permitted. Overall, we were able to collect data in sea states ranging from calm seas to sea state IV. Throughout the experiment data were gathered from a moored buoy that provided continuous monitoring of a high wave event (significant wave height > 4m) when the ship had to seek shelter. This moored buoy also contained an external

GPS package for comparison with the Datawell buoy. Overall, this field experiment has proven to be a success in that a large amount of data was collected for testing GPS wave measurement in a range of wave conditions.

This thesis is organized into six chapters. Chapter II describes the experiment, instrumentation, and data collection. Chapter III describes the data analysis procedures. Chapter IV compares measurements from different sensors (external GPS receivers and internal accelerometer or GPS systems) mounted on the same buoy to assess the accuracy of the sensors. This chapter focuses on three case studies that experienced varied sea states. Chapter V evaluates the performance of inexpensive prototype GPS buoys against the Datawell Waveriders (accelerometer and GPS buoys). Finally, Chapter VI presents a summary and the conclusions.

II. FIELD EXPERIMENT

A. INTRODUCTION

The main aim of this thesis is to compare prototype inexpensive GPS wave buoys built by the NPS Oceanography Department against the well-established Datawell Waverider buoys. Our experiment was conducted as part of the ONR HIRES DRI, a multi-institutional research project focused on determining the viability of using ship-based radars in conjunction with numerical models to predict the phase-resolved surface wave field around a surface vessel. This capability is important for the safety and effectiveness of naval operations and sea keeping in moderate to high winds and sea states. This project involved other research initiatives focused on the surface waves as well as the marine atmospheric boundary layer. A key part of this project is the validation of high-resolution marine radar/WaMoS (described in Chapter I) using in-situ buoy measurements and an airborne scanning lidar (ATM – airborne terrain mapper) that provides spatial-temporal maps of the sea surface and video imagery of breaking waves within the WaMoS footprint.

The R/P FLIP, which is based at the Scripps Institution of Oceanography (SIO) Marine Facility in San Diego, served as the stable platform required to collect detailed wind and wave measurements (Figure 1). Our experiments as well as some of the other projects under the same DRI were conducted from the support vessel R/V Robert Gordon Sproul also based at the SIO Marine Facility in San Diego (Figure 2). This thesis focuses on the data collected by the NPS group while underway from June 03 to June 29, 2010.

B. FIELD SITE

The site of the HIRES research proved to be an appropriate location to conduct this experiment with the varied sea state. All the buoy deployments in HIRES 2010 took place in the vicinity of the R/P FLIP. This research platform was moored at 38° 20.260 North 123° 25.691 West, roughly 16 miles off the California coast. The moored buoy, a

Datawell Waverider DWR-G7 was located at 38° 20.718 North 123° 25.509 West, approximately 1200 meters to the north of R/P FLIP (Figure 3). This location is on the continental shelf in waters roughly 160 meters deep.

The spring and early summer climate along the northern California coast is dominated by moderate to high wind from the northwest due to the periodic low-pressure systems that transit across the northern pacific. The vicinity of Bodega Bay tends to be a good site for air-sea interaction studies with a combination of wind waves from the northwest and lesser southeasterly swell waves contributing to relatively consistent 2-4 meter waves. The weather during this project (Figure 4) was episodic, with several 3-4 meter major wave events occurring during the experiment. These events common to the area offered the opportunity to deploy our buoys in a variety of sea conditions.

C. OVERVIEW OF EXPERIMENT

The NPS research team embarked aboard the R/V Spoul with 10 buoys. Seven of these buoys were Datawell Waveriders buoys of which two were the MK-II accelerometer buoy, two were the 0.7-m diameter GPS Waverider and three were the 0.4-m diameter GPS mini-Waverider buoys. The remaining three buoys were the prototype GPS buoys constructed by the NPS research team. All the buoys were equipped with one or more different GPS receivers that will be described in detail in the next section of this chapter (Table 2).

Over the course of the experiment, there were 13 day when 1-6 drifting buoys were deployed to gather surface wave measurements (Table 1). In these deployments, weather permitting, every attempt was made to deploy multiple buoys with different (accelerometer and GPS) sensor configurations to obtain a comprehensive data set for intercomparisons.

D. GPS SENSOR SYSTEMS

The main objective of this research is to determine the viability of using off-the-shelf GPS receivers to measure ocean surface waves. Here we will explain the different GPS units selected for the experiment based on their performance in pilot experiments.

The validation effort consists of two parts. First, by attaching the various GPS systems to the Datawell Directional Waverider MK-II buoy, we can test the basic GPS sensor performance by comparing it with the independent accelerometer-based measurement of the Datawell buoy. Then we will test the performance of prototype buoys with off-the-shelf GPS systems by deploying them in close proximity to Datawell buoys. Three different models of Datawell Waveriders are used in this study to facilitate intercomparisons between buoys of different sizes and accelerometer, and GPS-based buoys.

The configuration of the GPS systems used in this experiment is the outcome of an extensive study of available off-the-shelf hardware conducted through pilot tests with many different GPS units. As stated earlier, the goal is to examine the viability of GPS receivers to replace and/or augment more expensive buoys to enable surface vessels a more accurate measure of surface waves. Three GPS receivers were selected based on their precision, power needs, cost, and suitability for use on small buoys.

1. MR-350

The GlobalSat MR-350 is a self-contained, waterproof GPS receiver that supports both WAAS and EGNOS. This receiver is equipped with an active patch antenna and a SiRF Star III GPS chipset. The antenna is mounted through a bulkhead on a Pelican 1200 case and is connected to an Acumen DataBridge SDR2-CF inside the case that saves the data on a SD card. The system is powered by two LI-Ion batteries also located inside the case (Figure 5). These batteries were capable of powering the receiver and data logger for up to 5–7 days. This system identified as the MR-350 is attached to buoys 2, 3, and 5 (Table 2).

2. MMCX

The Magellan Mobile Mapper CX (MMCX) is a ruggedized handheld GPS unit that stores its data on a removable SD card and has an internal rechargeable battery. This unit is placed in a Pelican 1200 case for protection from the elements and to house additional LI-Ion batteries to Power an RF modem that transmit its position to a receiver on the research vessel. For greater accuracy, a Magellan NAP100 external antenna is attached to the top of the case. The RF antenna is also mounted to the top so that the buoy can be found with greater ease (Figure 6). This system identified as the MMCX is attached to buoys 2, 3, 9, 10, and 11 (Table 2).

3. GT-31

The Genie GT-31 is another waterproof handheld GPS unit (Figure 7). The GT-31 uses the SiRF III chipset and stores its data on internal flash memory with an option of removable SD card. The antenna is also an internal patch. This unit is mounted onto buoys 3, 4, 6, 7, and 8 (Table 2).

E. BUOYS

As discussed earlier the Datawell Waverider buoy is a widely used commercial wave buoy that has been validated as an accurate and reliable source for wave measurements (Barstow, 1991, O'Reilly et al., 1996). For this study, seven NPS Oceanography Department Waverider buoys were used. One buoy was moored so that it could gather wave data throughout the experiment. This moored buoy had one of the MR-350 systems mounted to the top plate, which due to limited battery life had to be replaced every 5–7 days (Figure 8). The other Waveriders were deployed free drifting as sea state allowed. Otherwise, they were lashed to the back deck of the R/V Robert Gordon Sproul (Figure 9). In addition to the Datawell Waveriders, three experimental buoys built at NPS using an MMCX GPS system, were deployed along with the Datawell buoys. A brief overview of the buoy hardware is given here.

1. Datawell Buoys

The Datawell Waverider MK-II is a spherical 0.9 meter diameter buoy (Figure 9). This buoy uses an accelerometer package together with a Hippy 40 heave-pitch-roll sensor to determine horizontal motion as well as surface displacement (Datawell, 2007). This buoy (and the newer version MK-III) is widely considered the instrument of choice where accurate directional ocean wave measurements are required (O'Reilly et al., 1996). The MK-II buoys (2 and 3) were deployed on 7 occasions during HIRES 2010 (Table 1).

During these deployments at least one or more of the MR-350, MMCX, and GT-31 GPS receivers were attached to provide independent measurements of ocean surface waves as well as accurately tracking the buoy's position.

The Datawell Waverider DWR-G7 is another spherical 0.7-meter diameter buoy. Other than the size difference, the DWR-G7 does not have accelerometers and instead uses a GPS receiver to measure waves. The Datawell Waverider GPS buoys use the Doppler shift in the GPS signal to determine the velocity of the GPS receiver relative to the satellites. When the GPS receiver moves toward (away from) the satellite it experiences an increase (decrease) in the GPS signal frequency that is proportional to the velocity of the buoy. Integrated over time this Doppler shift yields the relative buoy displacements. The Waverider's GPS system is purported to never need calibration and has been in commercial use since 2002 (Datawell, 2007). Two of these buoys were employed during HIRES 2010. Buoy 5 was the moored buoy discussed earlier in this chapter (Figure 10, 11). The other buoy 4 was deployed on three separate occasions with the GT-31 on board to provide additional surface wave measurements and buoy position tracking.

The third type of Datawell Waverider used for this study was the DWR-G4. This buoy is the smallest of the Datawell Waveriders at 0.4-meters. It is equipped with the same GPS sensor as the DWR-G7. During HIRES 2010, a subset of the three DWR-G4's were deployed a total of 9 times (Table 1). One or two GT-31 units were attached to each of the DWR-G4 buoys (Figure 12).

2. Prototype Buoys

For this study, two different types of buoys were built to hold the MMCX system. The goal was to build a simple buoy that would be low cost, lightweight, and easy to fabricate. During the field experiment, one or more of these buoys were deployed on 10 occasions. The prototype buoys occasionally had an additional GT-31 mounted to the top plate for independent wave measurements.

The first prototype was constructed by placing three Polyethylene closed cell foam discs each of slightly less diameter together. On the top and bottom of the foam there are two 1 cm thick Delrin (hard plastic) plates sandwiching the foam with a double-headed bolt holding them in place. On the top Delrin plate is a mounting bracket designed to hold the MMCX's Pelican case securely in the center (Figure 13). The MMCX's NAP100 antenna was attached to a metal bar that arcs over the pelican case that is also used as a handle (Figure 14). The bottom plate has an eyebolt that holds approximately 20 pounds of ballast chain.

The second prototype is a simple 0.4-meter diameter sphere composed of foam enclosed in a hard plastic shell with a hole through the center (Figure 15). In the same fashion as the first prototype, a double-headed screw holds a Delrin plate on the top and an eyebolt on the bottom. The MMCX is fastened to the top plate, while approximately 20 pounds of ballast chain is hung from the eyebolt to keep the buoy upright.

Date	Buoys	GPS Receivers	Deployment Times (UTC)
5 June	2	MR350	21:25-01:50
6 June	2 10	MR350, MMCX MMCX	20:33-01:30
8 June	6 7	GT31 (2) GT31 (2)	22:31-01:44
9 June	2 6 7 10 11	MR350, MMCX GT31 (2) GT31 (2) MMCX MMCX	18:25-01:52
12 June	2 4 6 7 10	MMCX GT31 GT31 GT31 (2) MMCX	22:53-04:47
17 June	7 8 10 11	GT31 (2) GT31 (2) MMCX MMCX	20:00-05:10
18 June	8 10 11	GT31 (2) MMCX MMCX	00:20-02:00
20 June	8 9 10 11	GT31 (2) MMCX MMCX MMCX	20:40-00:05
21 June	8 9 10 11	GT31 (2) MMCX MMCX MMCX	19:40-00:35
23 June	3	MR350, MMCX, GT31 (2)	17:31-22:20
24 June	3 4 10 11	MR350, MMCX, GT31 GT31 MMCX MMCX	20:33-00:55
25 June	3 4 5 8 10 11	MR350, GT31 GT31 GT31 (2) GT31 (2) MMCX MMCX	20:04-02:20
27 June	8 9 10 11	GT31 (2) MMCX MMCX, GT31 MMCX, GT31	17:32-23:02

Table 1. Summary of wave buoy deployments during HIRES 2010.

Buoy #	Serial #	Description	Complement	Drifter/Moored
2	30348	MK-II 0.9M	MMCX MR-350	Drifter
3	30157	MK-II 0.9M	MMCX MR-350 GT-31	Drifter
4	53011	DWR-G7 0.7M	GT-31	Drifter
5	53014	DWR-G7 0.7M	MR-350	Moored
6	55018	DWR-G4 0.4M	GT-31	Drifter
7	55019	DWR-G4 0.4M	GT-31	Drifter
8	55043	DWR-G4 0.4M	GT-31	Drifter
9	OC-1	Proto-1	MMCX	Drifter
10	OC-2	Proto-1	MMCX	Drifter
11	OC-3	Proto-2	MMCX	Drifter

Table 2. Identification of NPS wave buoys used during the HIRES 2010 experiments.

Figure 1. R/P FLIP, picture taken June 9, 2010 (by David Colbert).

Figure 2. R/V ROBERT GORDON SPROUL
(http://shipsked.ucsd.edu/Ships/Robert_Gordon_Sproul/images/sproul_dock.jpg)

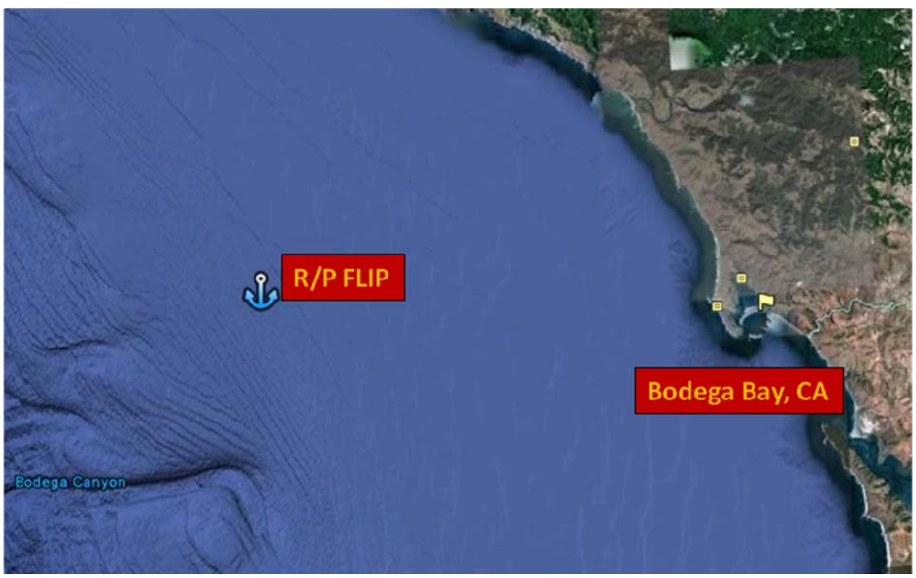

Figure 3. Location of R/P FLIP, for the HIRES 2010 experiment off the coast near Bodega Bay, CA.

Figure 4. R/P FLIP, moored in rough seas off the coast near Bodega Bay, CA.

Figure 5. The GlobalSat MR-350 sensor system. Inside the Pelican 1200 case the two LI-Ion batteries are being connected to the Accumin datalogger and MR-350 GPS receiver moments before the buoy is launched and moored north of R/P FLIP.

Figure 6. The Magellan MMCX sensor system with the Magellan NAP100 GPS antenna and RF antenna visibly mounted on the Pelican 1200 case. The MMCX handheld is inside.

Figure 7. One of the many LocoSys GT-31 GPS receivers used in the experiment.

Figure 8. NPS buoy 5, recovery aboard the R/V Robert Gordon Sproul, to replace batteries in the GlobalSat MR-350.

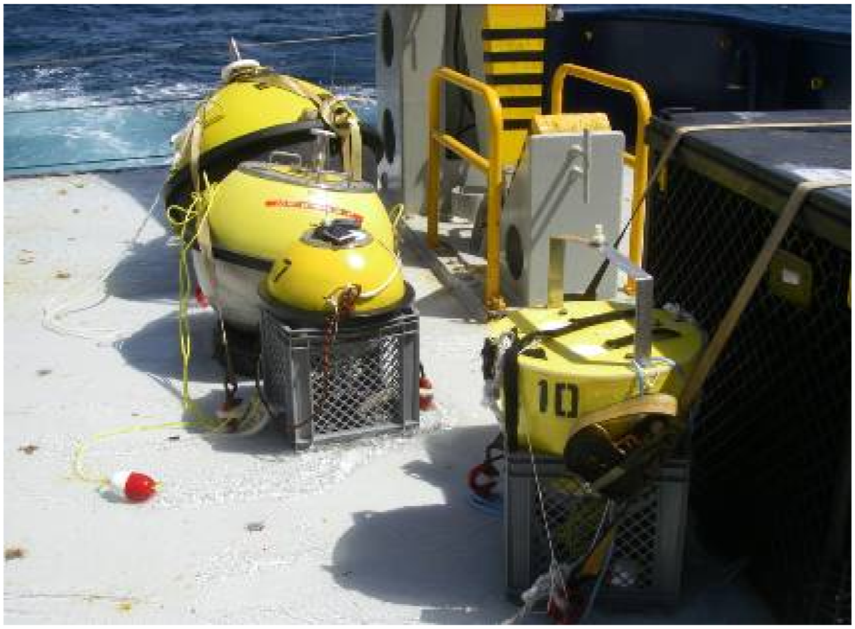

Figure 9. From left to right, buoy 3 (0.9 m MK-II), buoy 4 (0.7m DWR-G7), buoy 7 (0.4 m DWR-G4), and prototype buoy 10 lashed to the deck of the R/V Robert Gordon Sproul.

Figure 10. NPS buoy 5. Picture taken as the DWR-G7 was being moored off the coast near Bodega Bay, CA, June 5, 2010.

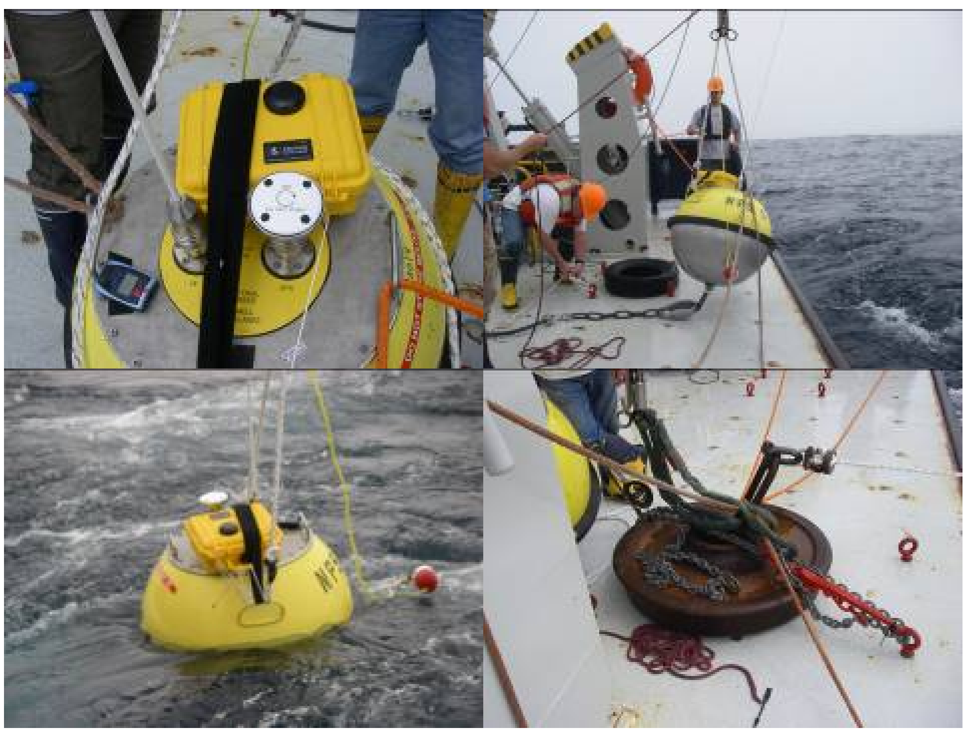

Figure 11. NPS buoy 5, deployed from the R/V Robert Gordon Sproul, June 5, with the MR-350 and GT-31 systems attached. This buoy was moored for collecting continuous wave data. (Top left) Image of GPS systems strapped to the top, (top right) buoy deployment, note the mooring line dangling off the bottom, (bottom left) in the water before release, (bottom right) mooring anchor.

Figure 12. NPS buoy 6, recovery on board the R/V Robert Gordon Sproul, June 5, with two LocoSys GT-31 GPS receivers attached.

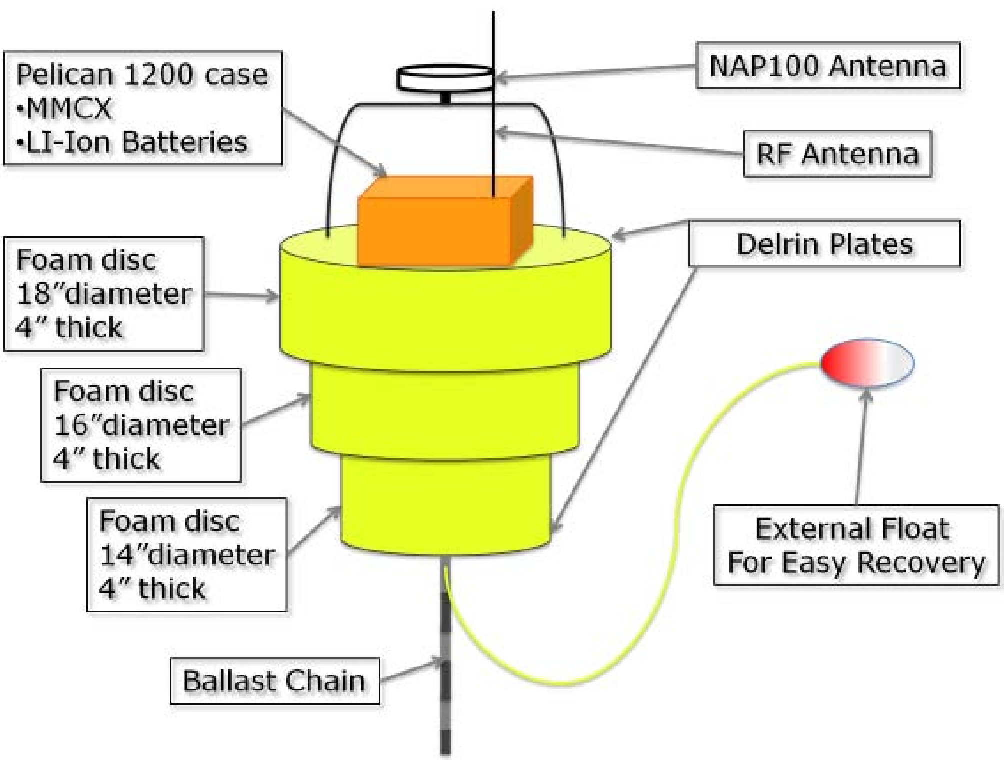

Figure 13. Schematic of Prototype Buoy 1.

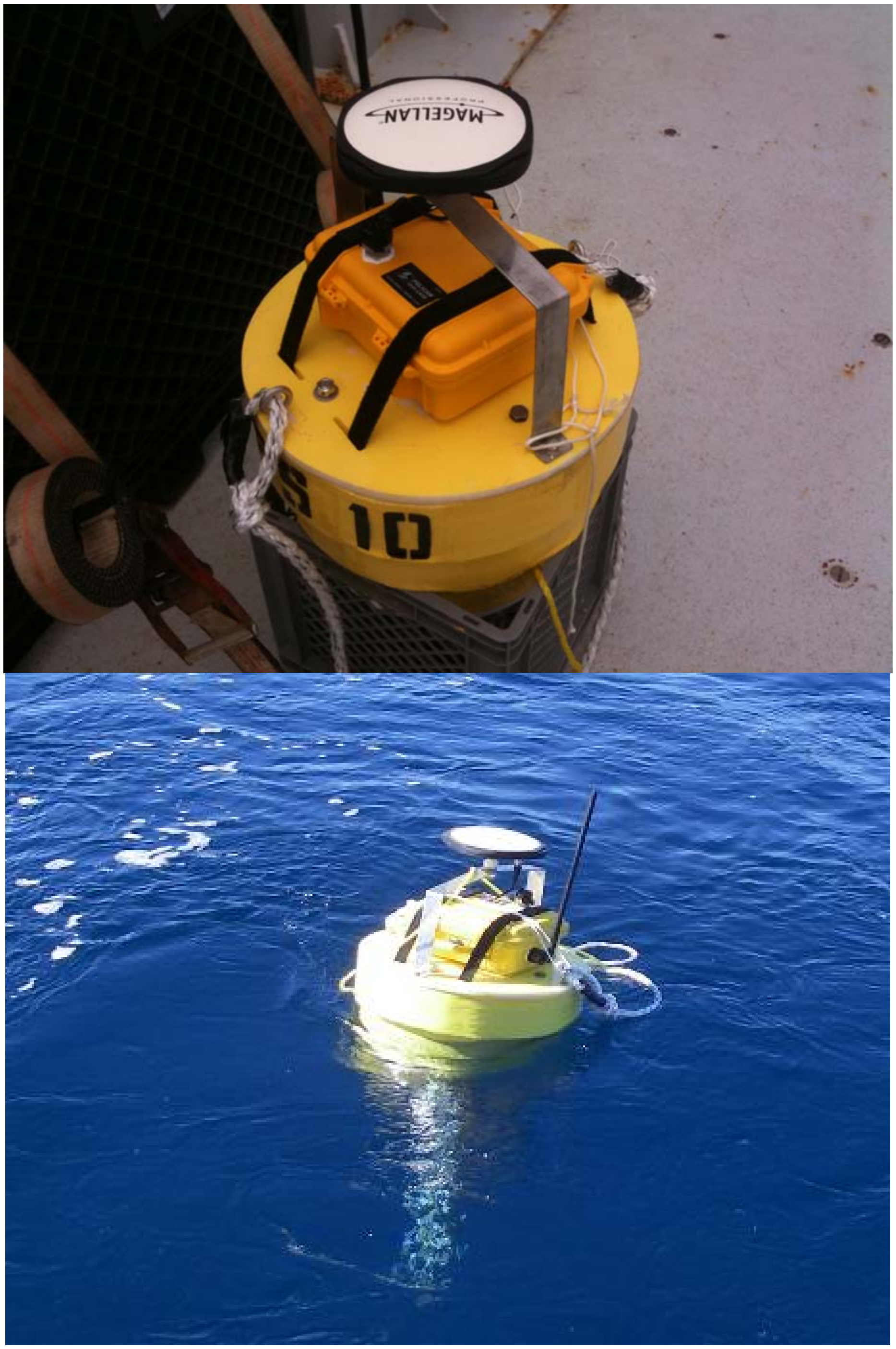

Figure 14. NPS buoy 10. Top picture: GPS prototype buoy 10 equipped with Magellan MMCX. Bottom picture: Buoy 10 deployed from the R/V Robert Gordon Sproul, June 5, with the MMCX system. Note the ballast chain reflected beneath the buoy.

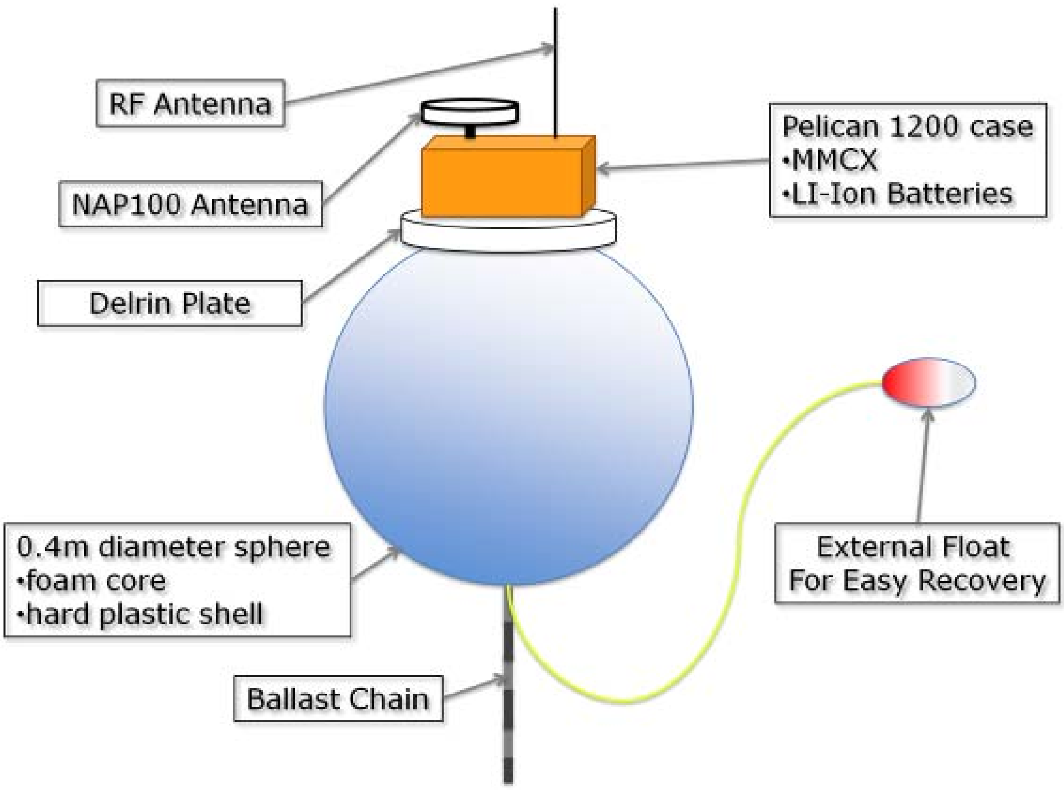

Figure 15. Schematic of Prototype Buoy 2.

III. DATA ANALYSIS

A. INTRODUCTION

The wave measurements used for this research were collected during the HIRES 2010 experiment from 5–27 June 2010. All the data were recorded onboard the buoys with the exception of buoys 2 and 3 that used an HF telemetry link to the research vessel. Much of the initial analysis for this project was conducted in the field by the NPS team while underway on the R/V Robert Gordon Sproul. The quality control of the data was completed using MATLAB programs created by Professor T. H. Herbers and Paul Jessen.

It is important to note that the drifting buoy deployment and retrieval operation typically took from a half hour to several hours (i.e., in rough weather conditions). The times listed in Table 1 cover the period from the first buoy deployed to the last buoy retrieved. To intercompare different buoys a shorter time interval was selected that covers the period when all buoys were in the water.

B. QUALITY CONTROL

Occasionally the data from both the accelerometer and GPS sensors will spike and give inaccurate readings. These spikes in the data are quite obviously erroneous because large sudden jumps or dips in sea surface height are not physical. These spikes were filled in through linear interpolation. Additionally GPS receivers are known to lose their position intermittently. This dropout can be caused by the loss of line of sight with individual satellites. In addition, when the receiver is covered by splashing waves the GPS unit will lose GPS signal and take some time to recover. The Datawell GPS units have their own software that is used to isolate erroneous data (Datawell, 2007). This program will also linearly interpolate the data gaps.

The Datawell Waveriders do not have an accurate time stamp on their recorded data (Datawell, 2007). Since each buoy was equipped with one or more GPS receivers, we were able to correct their timing error through cross-correlation between the Datawell buoy and an attached GPS unit. The buoy time-series were then shifted to obtain maximum correlation with the GPS time-series. The Datawell buoys and the GPS units had different sampling rates of 1.28 Hz and 1 Hz respectively. The buoy time-series were linearly interpolated on the GPS sampling interval so that all data sets had the same sampling rate of 1 Hz.

C. ANALYSIS

1. Spectral Analysis

The spectral analysis was conducted through Matlab. This analysis was used to compute both vertical and horizontal displacement spectra. For the vertical spectra, we used the vertical displacement of the buoy and for the horizontal spectra, we used the sum of the spectra of the buoys horizontal displacements. In the linear deep-water approximation, the vertical and horizontal wave orbital displacement spectra are equal and thus provide an estimate of the wave height spectrum (Bascom, 1964). The spectral analysis was performed between 0.04 Hz and 0.4 Hz. This range was chosen to include the dominant sea and swell wave energy.

Before the spectral analysis was executed, we removed a 60-second moving-average to filter out low frequency motion in the GPS and Buoy signals. The spectral analysis was performed using Fast Fourier Transform of segments with a length of 2048 samples with a Hanning window and 50% overlap. The spectra were subsequently smoothed by merging 13 bands. The resolution of the final smoothed spectra was 0.0063 Hz.

The accelerometer buoy uses a magnetic compass to determine wave direction. The horizontal displacements of the buoy were rotated by 14.6° to account for the magnetic declination at the field site.

2. Directional Analysis

In this study, we use the mean propagation direction θ and a measure of directional spreading of wave energy σ, as functions of frequency to characterize the directional properties of waves. These parameters can be expressed in terms of either first or second order Fourier moments of the directional wave spectrum (e.g., Kuik et al., 1988; Herbers et al., 1999).

Estimates based on first order moments are given by

$$\tan\left(\theta(f)\right)=\frac{b_1\left(f\right)}{a_1\left(f\right)}, \tag{1a}$$

$$\sigma\left(f\right)=\sqrt{2\left(1-\sqrt{a_1\left(f\right)^2+b_1\left(f\right)^2}\right)}, \tag{1b}$$

where $a_1\left(f\right)$ and $b_1\left(f\right)$ are obtained from the Co-$\left(C\right)$ and quadrature $\left(Q\right)$ spectra of vertical $\left(z\right)$ and horizontal $\left(x,y\right)$ displacement time-series,

$$a_1\left(f\right)=\frac{Q_{zx}\left(f\right)}{\left\{C_{zz}\left(f\right)\left[C_{xx}\left(f\right)+C_{yy}\left(f\right)\right]\right\}^{1/2}}, \tag{2a}$$

$$b_1\left(f\right)=\frac{Q_{zy}\left(f\right)}{\left\{C_{zz}\left(f\right)\left[C_{xx}\left(f\right)+C_{yy}\left(f\right)\right]\right\}^{1/2}}. \tag{2b}$$

Estimates based on second order moments are given by

$$\tan\left(2\theta(f)\right)=\frac{b_2\left(f\right)}{a_2\left(f\right)} \tag{3a}$$

$$\sigma\left(f\right)=\sqrt{\frac{1}{2}\left(1-\sqrt{a_2\left(f\right)^2+b_2\left(f\right)^2}\right)} \tag{3b}$$

where $a_2\left(f\right)$ and $b_2\left(f\right)$ are obtained from the horizontal displacement data only,

$$a_2\left(f\right)=\frac{C_{xx}\left(f\right)-C_{yy}\left(f\right)}{C_{xx}\left(f\right)+C_{yy}\left(f\right)} \tag{4a}$$

$$b_2\left(f\right)=\frac{2C_{xx}\left(f\right)}{C_{xx}\left(f\right)+C_{yy}\left(f\right)}. \tag{4b}$$

The latter estimates have the advantage that they do not depend on vertical displacement data, which (as discussed in later chapters) for some GPS receivers is noisier than the horizontal displacement data.

3. Wave Parameters

To characterize the sea state we use standard bulk wave parameters: significant wave height (Hs), dominant wave period (Tp), and dominant wave direction (θm). Significant wave height, the average wave height (trough to crest) of the one-third largest waves approximately equals 4 times the standard deviation of sea surface height and was estimated from the vertical displacement spectra in the swell-sea frequency range 0.04-0.4 Hz. Dominant wave period is the period that corresponds to the frequency of maximum energy and the dominant wave direction refers to the mean direction at the peak period.

4. Wave Conditions and Case Study Selection

Wave conditions at the field site varied considerably throughout the field experiment. Time-series of the bulk wave parameters estimated from the moored buoy for the 19-day period it was deployed are shown in Figure 16. There were at least four different high seas events with Hs exceeding 3m during this timeframe. During these heavy seas events we were not able to deploy our wave buoys due to safety concerns for the vessel and crew. Also of note is the mean wave direction on June 9 when the northwesterly winds eased allowing long period southwesterly swell to dominate the wave field, causing a large change in mean wave direction and a corresponding increase in peak period.

Five case studies are presented in this thesis. In the selection of the cases, multiple factors were considered. For the intercomparison between the different GPS receivers and accelerometer sensors, it was necessary to select days when both the Magellan MMCX and the GlobalSat MR-350 where deployed together on a Datawell MK-II Waverider buoy. Also it was important to cover different conditions such as benign swell conditions in case 1, mixed swell-sea conditions in case 2, and energetic local seas in case 3. For the comparison of Datawell Waverider buoys and prototype buoys it was important to select cases that involved as many buoys as possible. Once again, sea state was a factor in case selection. In Figure 16, the cases selected for this research are highlighted with a red line. Note that case 5 occurred after the moored buoy was recovered.

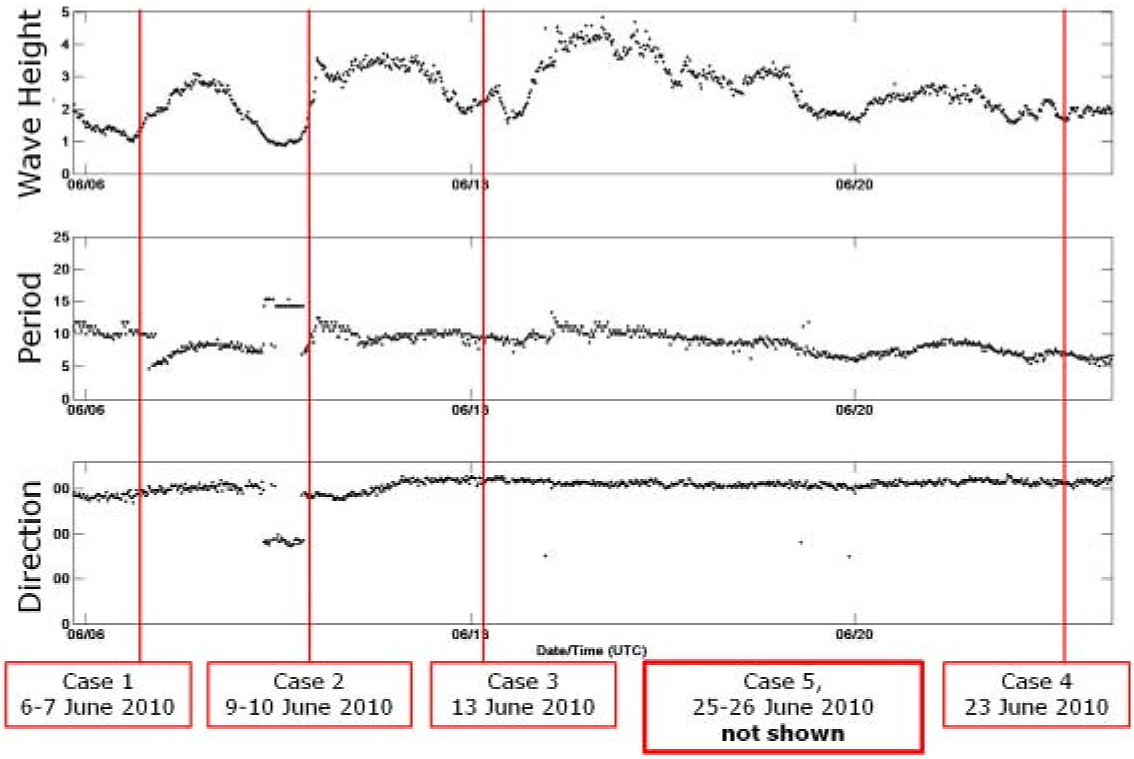

Figure 16. Data from the moored Datawell 0.7 m Waverider buoy with the GlobalSat MR-350 GPS receiver, for the entire deployment period June 5–24. From top to bottom time series of Hs, Tp and θm. The 5 cases examined for this project are highlighted in red. Note case 5 occurred after the buoy was recovered.

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IV. INTERCOMPARISON BETWEEN GPS AND ACCELEROMETER SENSORS

A. INTRODUCTION

The Datawell Waverider MK-II accelerometer buoy is the platform used here to study the viability of using inexpensive GPS receivers as wave measurement sensors. This buoy is considered the standard in surface wave buoys (O'Reilly et al., 1996) and offers an excellent basis for this comparative research. The Magellan MMCX and GlobalSat MR-350 GPS systems were attached externally to the MK-II buoy and thus measure identically the same waves (Figure 17). Spectra of vertical displacement, horizontal displacement, and the transfer function between the vertical and horizontal displacement are compared to assess the response of the GPS sensors to waves. Next, we will assess the GPS unit's skill in resolving mean wave direction and directional spreading as functions of frequency, again using the Datawell measurements as the "ground truth." Estimates based on both first order moments and second order moments are evaluated to examine the sensitivity to errors in GPS altitude measurements. The time for all of these experiments were taken in Coordinated Universal Time (UTC) and will be displayed in the 24-hour clock.

B. CASE STUDIES

1. Case 1 – Benign Swell

On June 6, 2010, Datawell buoy 2 equipped with a Magellan MMCX and a GlobalSat MR-350 collected wave measurements for 4 hours from 2100 to 0100 UTC. During this time significant wave height was steady at 1.5 meters with a peak period of 10 seconds and constant wave direction from 300° (Figure 16).

An example 5-minute time series of vertical displacement, the horizontal east displacement, and the horizontal north displacement is shown in Figure 18. The vertical displacement time series of the buoy accelerometer sensor and the MMCX are in good agreement, while the MR-350 is not. The horizontal displacement time series shows good agreement among all three sensors.

The vertical displacement spectrum (Figure 19) of the MMCX is in good agreement with the buoy in the energetic part of the spectrum. Below 0.05 Hz and above 0.30 Hz the MMCX spectrum is biased high by as much as a factor of 2. In contrast the MR-350 shows a large negative bias throughout the spectrum. In the horizontal displacement spectra (Figure 19), both the MMCX and the MR-350 show good agreement below 0.2 Hz. Here the MMCX diverges from the accelerometer sensor and the MR-350 at high frequencies. In deep water, the transfer function between vertical and horizontal displacement is equal to 1 in linear wave theory. The buoy estimates are in excellent agreement with this prediction while the MMCX follows the prediction in the energetic part of the spectrum. The agreement is poor for the MR-350. This is due to the large errors in the vertical displacement measurements that are probably the result of multi-path reflection associated with the MR-350's small bulkhead antenna (Chapter II).

Mean wave direction based on both first and second order moments are in good agreement for all sensors. Directional spread estimates based on second order moments also agree well, but large discrepancies are noted for the MR-350 estimates based on first order moments, reflecting the large errors in vertical displacement measurements.

2. Case 2 – Mixed Swell-Sea

On June 9, 2010, buoy 2 is again deployed with the MMCX and MR-350 (Table 1) collecting wave measurements from 2200 to 0000 UTC. Here wave height builds steadily from 1.1 meters to 1.4 meters with a peak period fluctuating between the 6 s wind sea peak and the 15 s swell peak. Wave direction varied between 298° and 190° due to the mixed southerly swell and northwesterly sea (Figure 16).

In Figure 20, a 5-minute displacement time series reveals the same pattern seen in case 1, with generally good agreement between the three sensors except for the large discrepancies in the MR-350 vertical displacement.

In both the vertical and horizontal displacement spectra we find the same trends as in case 1 (Figure 21) with the MR-350 under-estimating vertical displacement spectral levels at all frequencies by about a factor of 2. The MMCX is in close agreement with the accelerometer sensor in recognizing the bi-modal swell seas and obeys approximately the linear transfer function between the vertical and horizontal displacement (Figure 21).

The mean wave direction based on both first and second order moments again show good agreement for all sensors. Similar to case 1, directional spread discrepancies are seen for the MR-350 for the first order moment estimates, but good agreement for the second order moment estimates, while both the MMCX estimates agree well with the buoy estimates.

3. Case 4 – Wind Seas

Datawell buoy 3 was deployed on June 23, 2010 equipped with both the MMCX and MR-350 (Table 1). Wave measurements were collected from 1800 to 2200 UTC. The significant wave heights remained in a narrow 1.8 - 2 meters range with a peak wave period of 6 seconds and direction from 310° (Figure 16).

The 5-minute sample time series for the wind seas case is again very similar to the time series found in cases 1 (Figure 22).

Once again, the MMCX is in agreement with the accelerometer sensor from 0.05 Hz to 0.30 Hz in the vertical displacement spectrum (Figure 23) while the MR-350 continues to show the same low bias. In the horizontal displacement spectra (Figure 23) both GPS receivers agree with the accelerometer sensor. The transfer function between the vertical and horizontal displacement spectra (Figure 23) shows close agreement with linear theory for the accelerometer and MMCX sensors while the MR-350 is again biased low.

Mean wave direction estimates from the MR-350 based on first order moments show significant divergence from the other sensors at higher frequencies while the second order moment estimates are in good agreement. In the directional spread estimates from first order moments, we find similar discrepancies as in cases 1 and 2. The spread estimates from second order moments are in close agreement for all sensors.

C. RESULTS

Throughout the intercomparison of multiple sensors on the Datawell 0.9m accelerometer buoy we find agreement between the buoys accelerometer sensor and the Magellan MMCX and the GlobalSat MR-350 GPS sensors in the energetic part of the spectrum. There is a significant low bias in the GlobalSat MR-350 in the vertical displacement spectra, but this same bias is not found in the horizontal displacement spectra. The Magellan MMCX shows consistent agreement with the accelerometer sensor in both the vertical displacement and the horizontal displacement spectra, but some evidence of noise affecting the higher frequencies, especially in the horizontal displacement spectra.

Mean wave direction and directional spread estimates of the Magellan MMCX are in good agreement with the accelerometer estimates. The MR-350 also yields good agreement except for directional spread estimates, that are biased high if the first-order moments method is used that is based on both vertical and horizontal displacement. The agreement is much improved for the second moment estimates based only on horizontal displacements. As explained earlier this is possibly due to the multi-path reflection with the small bulkhead antenna mounted on top of the Pelican case. The MMCX does not have this limitation because a larger, higher resolution Magellan NAP100 antenna was used, raised above the Pelican case housing of the GPS unit. Although the MR-350 clearly does not provide usable vertical wave elevation measurements, we can still obtain accurate wave height estimates from the measured horizontal orbital wave displacements, which, in deep water linear wave theory, have the same magnitude as the vertical displacements.

A possible solution to the vertical displacement error in the MR-350 could be to mount a small metal sheet under the MR-350's patch antenna. This could reduce the multi-path reflection error as it did in a study of low-cost handheld GPS systems measuring surf-zone currents (MacMahan et al., 2009).

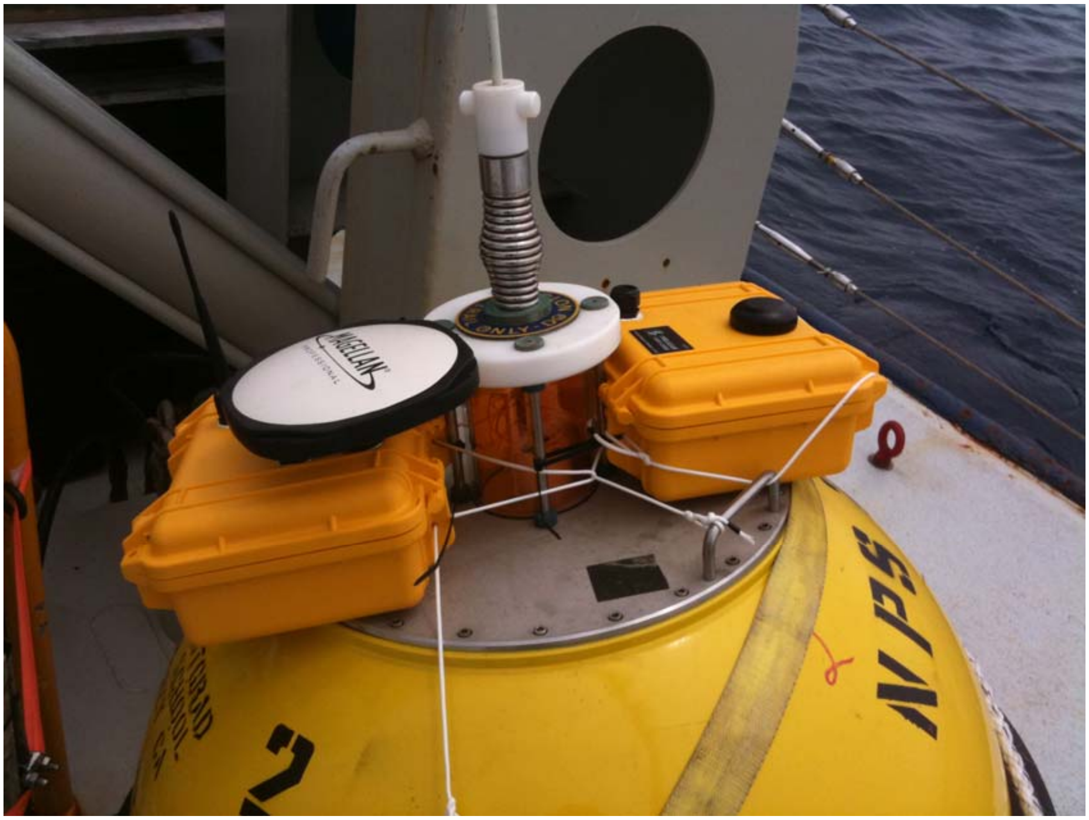

Figure 17. Datawell MK-II accelerometer buoys equipped with the Magellan MMCX and GlobalSat MR-350 GPS systems.

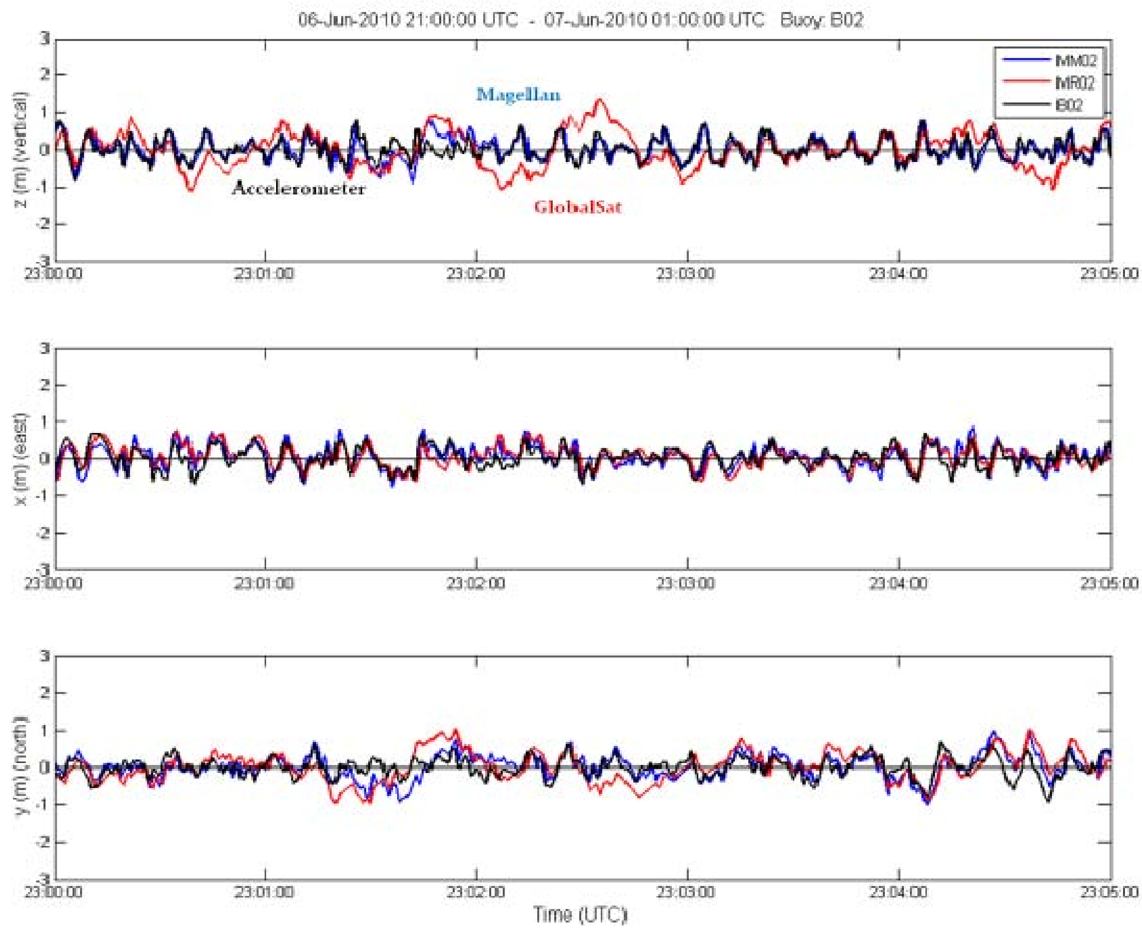

Figure 18. 06 June 2010, example 5-minute time series comparison between Datawell Waverider MK-II accelerometer measurements, and Magellan MMCX and GlobalSat MR-350 GPS measurements. From top to bottom: vertical displacement, horizontal displacement (east), and horizontal displacement (north). The accelerometer sensor is shown in black, Magellan MMCX blue, and GlobalSat MR-350 red.

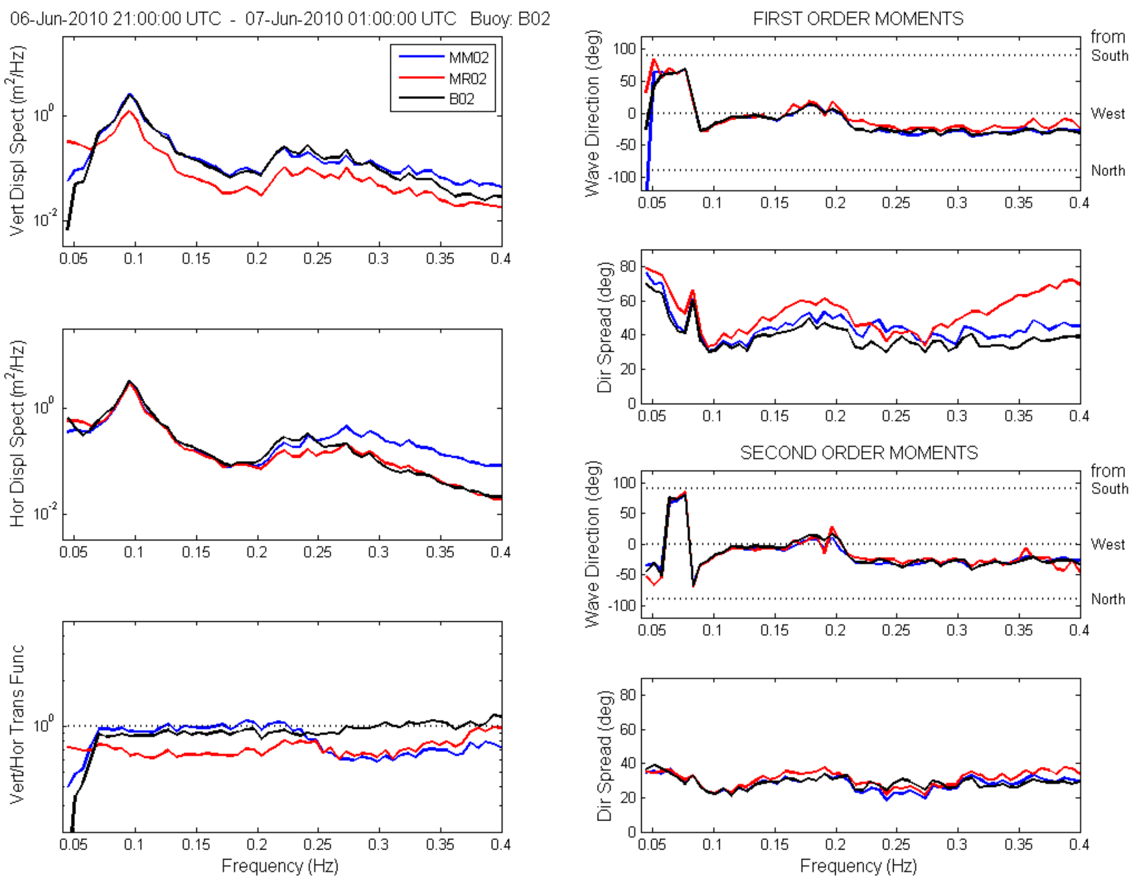

Figure 19. 06 June 2010, intercomparison between Datawell Waverider MK-II, Magellan MMCX, and GlobalSat MR-350. Left panels from top to bottom: vertical displacement spectra, horizontal displacement spectra, and vertical/horizontal transfer function (the dotted line indicates the deep water linear theory value of 1). Right Panels from top to bottom: mean wave direction spectra and directional spreading spectra based on first order moments, followed by the same results based on second order moments.

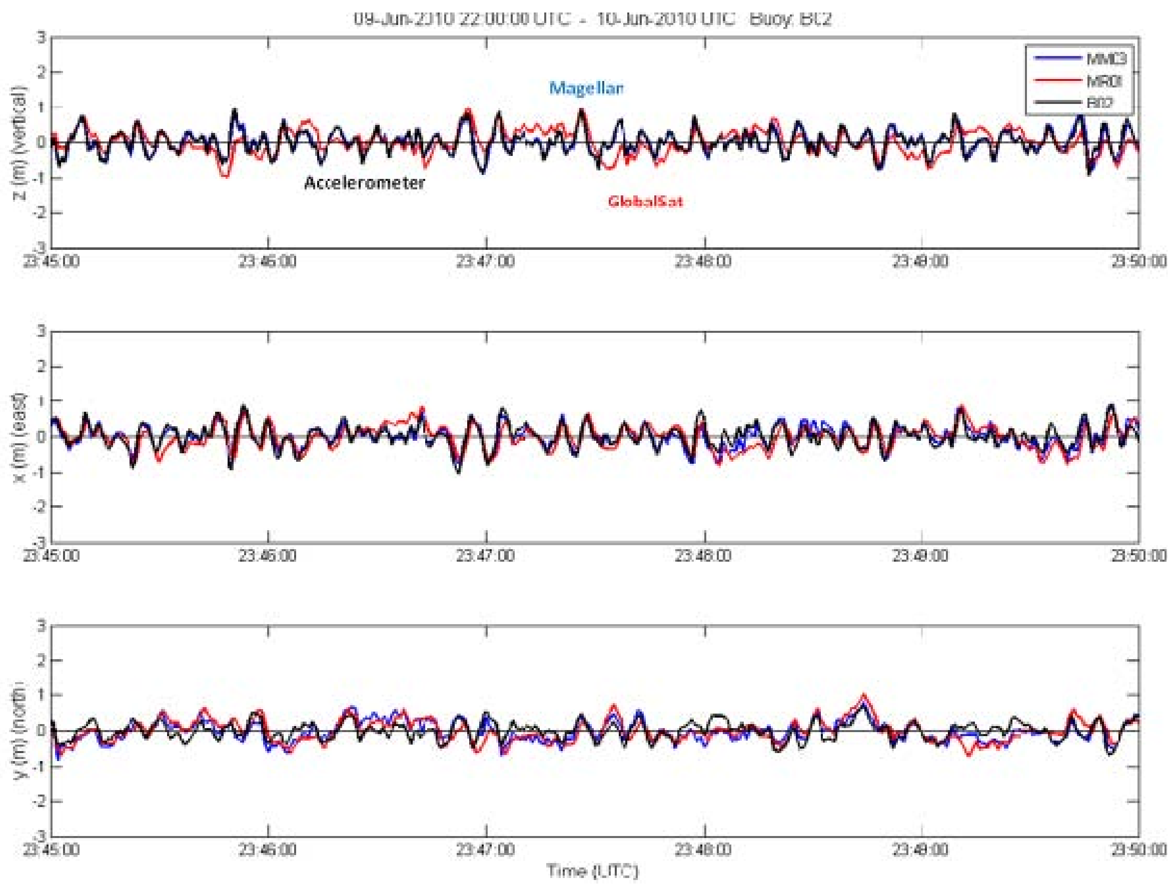

Figure 20. 9 June 2010, example 5-minute time series comparison between Datawell Waverider MK-II accelerometer measurements, and Magellan MMCX and GlobalSat MR-350 GPS measurements. (same format as Figure 18).

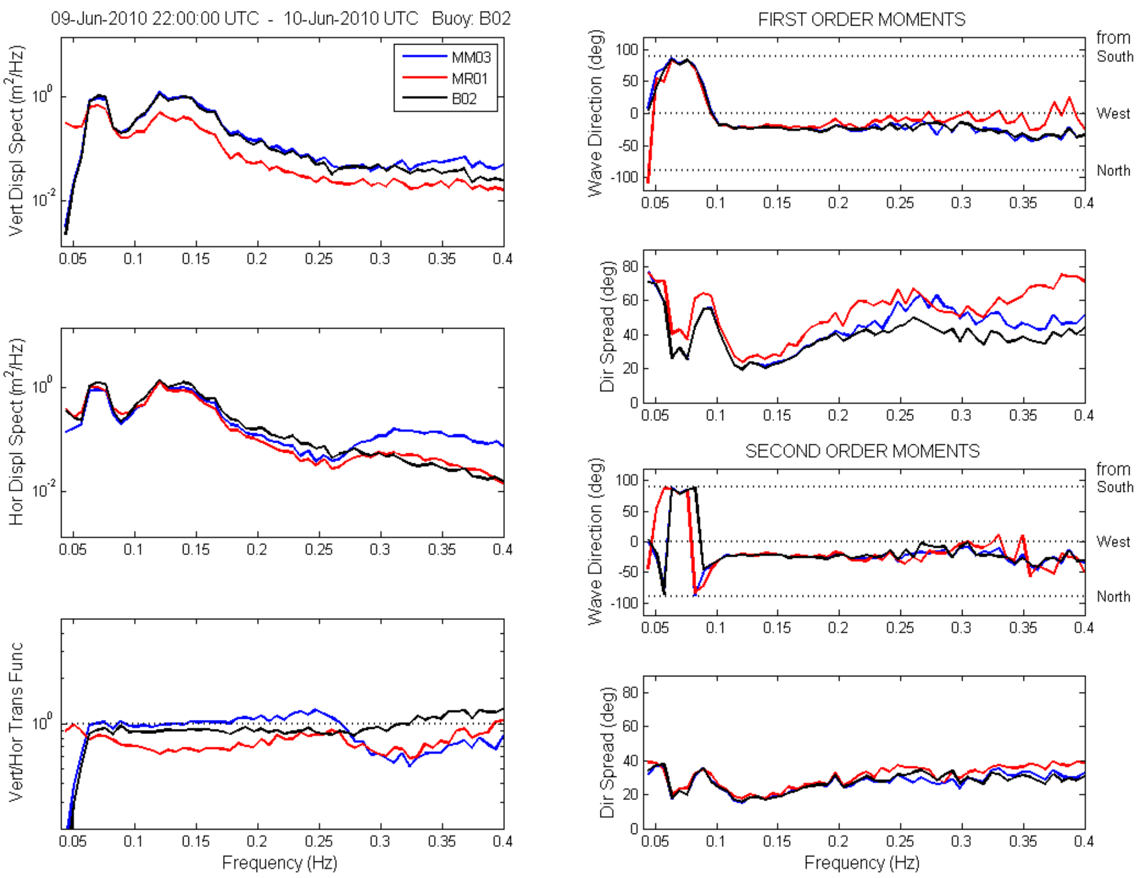

Figure 21. 09 June 2010, intercomparison between Datawell Waverider MK-II, MMCX, and MR-350 (same format as Figure 19).

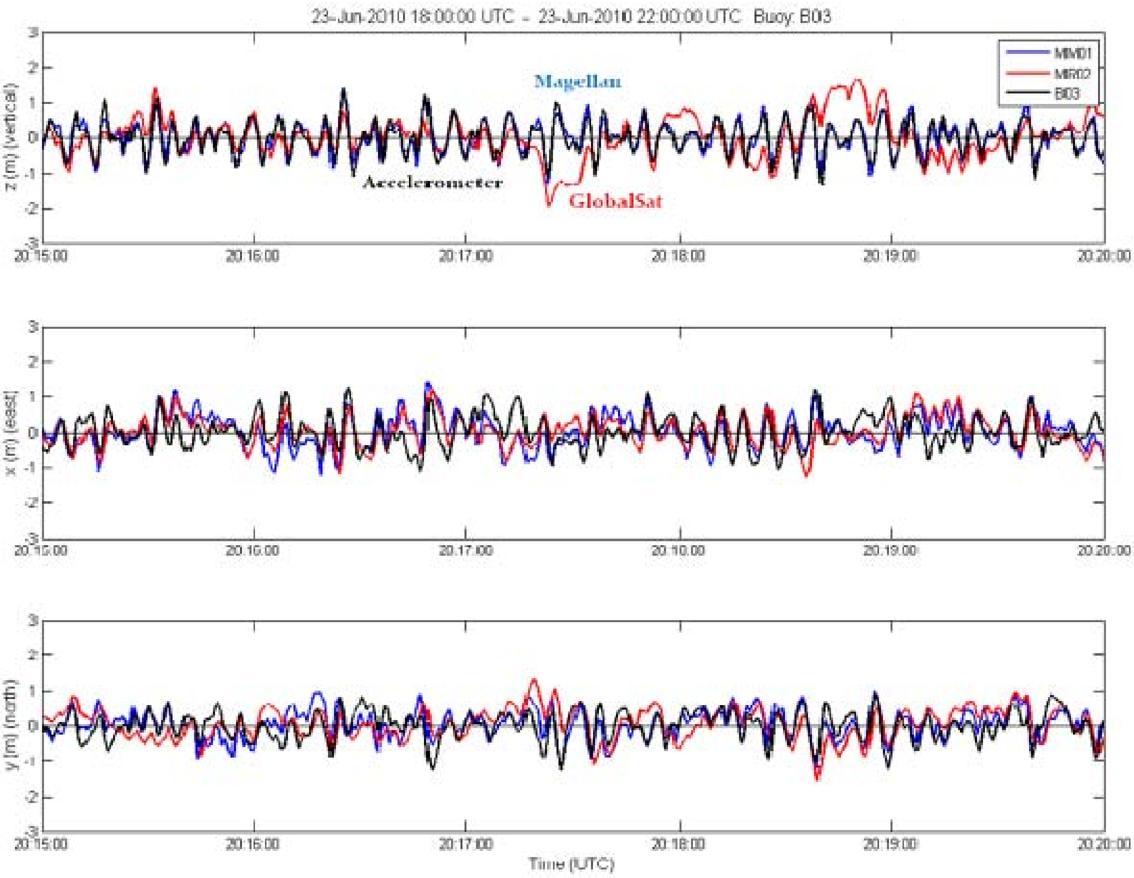

Figure 22. 23 June 2010, example 5-minute time series comparison between Datawell Waverider MK-II accelerometer measurements, and Magellan MMCX and GlobalSat MR-350 GPS measurements. (same format as Figure 18).

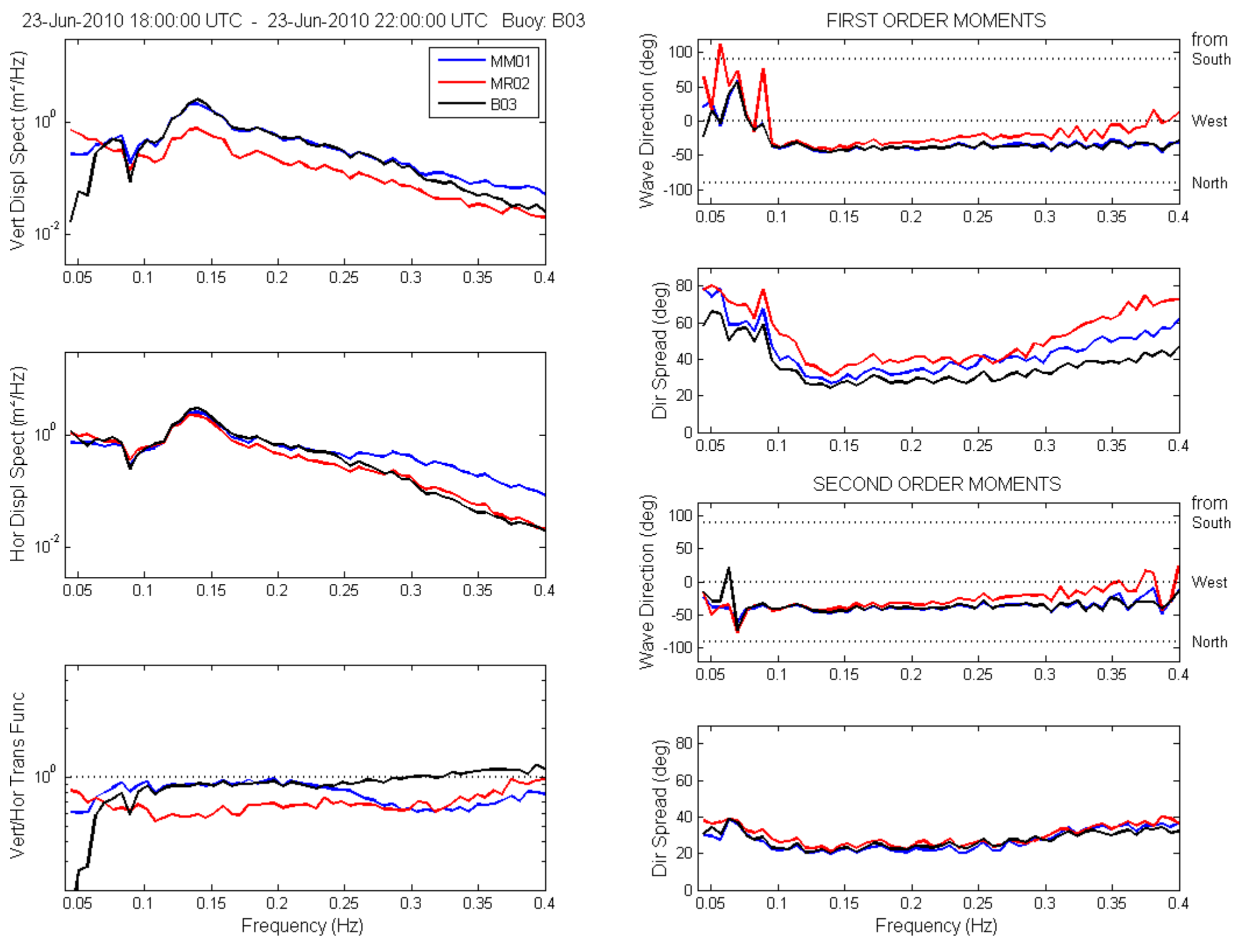

Figure 23. 23 June 2010, intercomparison between Datawell Waverider MK-II, MMCX, and MR-350 (same format as Figure 19).

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V. COMPARISON BETWEEN GPS PROTOTYPE BUOYS AND DATAWELL WAVERIDER BUOYS

A. INTRODUCTION

Throughout the HIRES experiment clusters of drifting buoys were deployed to facilitate intercomparison between the different types of Datawell buoys as well as the prototype inexpensive GPS buoys. The prototype buoys equipped with the Magellan MMCX were deployed together with three different Datawell Waverider buoys, the MK-II (0.9-m diameter accelerometer), DWR-G7 (0.7-m diameter GPS), and the DWR-G4 (0.4-m diameter GPS). The prototype buoy spectra are also compared to the moored DWR-G7 buoy that was discussed in detail in Chapter II.

There are three individual deployments that are examined here. The case studies occurred 9 June, 12 June, and 25 June. These cases were chosen in an attempt to record data from as many buoys as possible. It was also important to gather data from different wave events. The wave measurement data collected are evaluated through their wave spectra, mean wave direction, and directional spreading (both estimated using the standard first order moment method). The predominate drift track for all the buoys was to the south-south east.

B. CASE STUDIES

1. Case 2 – Mixed Swell-Sea

On June 9, 2010, between 2300 and 0030 UTC, 6 buoys were deployed, including all the different Datawell models, one MK-II, one DWR-G7, and two DWR-G4, as well as two different prototype buoys (Table 2). Wave conditions for this case are described in Chapter IV.

Review of the June 9 data reveals good agreement between the deployed buoys (Figure 24). All the buoys clearly resolved the bi-modal sea state in the wave spectrum, evident in the two distinct peaks. The prototype buoys diverge from the Datawell buoys at frequencies above 0.25 Hz where wave energy levels are relatively low. The higher spectral levels in the spectral tail are indicative of an elevated noise level. Similar discrepancies were noted in the previous intercomparison of the MMCX GPS receivers with the accelerometer sensor when both instruments recorded waves from the same buoy, suggesting the errors reflect the intrinsic noise limitation of the MMCX receiver rather than a buoy response issue.

In the mean wave direction, all the buoys are in good agreement, resolving low frequency swell from the south and higher frequency wind seas consistently from the west (Figure 24). The directional spread of the buoys in this case show agreement in the dominant part of the spectrum, while at high (> 0.2 Hz) frequencies the prototype buoys diverge with a positive bias, probably owing to the higher noise levels seen in the MMCX wave spectrum estimates.

Significant wave height estimates of the five drifting buoys varied between 1.31-m and 1.46-m indicating good agreement between all buoys including the prototype buoys (1.35-m and 1.38-m). The moored DWR-G7 buoy had the lowest measurement at 1.29-meters, possibly owing to spatial variations in the wave conditions.

2. Case 3 – Wind Dominated Sea

On June 12, from 0135 to 0300 UTC, five buoys were deployed in the waters to the southeast of the R/P FLIP. This day also offers a representative of all three Datawell buoys: one MK-II, one DWR-G7, and two DWR-G4 as well as prototype buoy 10 (Table 1). During this time wave height varied from 2.0 to 2.5 meters with a peak period at 10 seconds and wave direction shifting from 320° to 300° (Figure 16).

Close agreement between all deployed buoys is evident in the wave spectrum estimates (Figure 25). The mean wave directions are in good agreement as well with a predominate direction from the northwest. The directional spread estimates agree at the dominant wave frequencies and diverge in the tail of the spectrum where the prototype buoy is biased high as in case 2.

The MK-II has the highest significant wave height at 2.26-meters followed by the DWR-G7 at 2.15-meters, then prototype buoy 10 at 2.11-meters. The two DWR-G4s measure significant wave height at 2.06 and 2.03-meters. It should be noted that buoy 2 drifted farther south than the other buoys, and this separation may have contributed to some variation in the wave conditions.

3. Case 5 – Mixed Swell-Wind Sea

On June 25, 2010, five buoys were deployed and wave measurements are evaluated for 4 hours from 2040 to 0030 UTC. Three Datawell buoys the MK-II, DWR-G7, DWR-G4 and both GPS prototype buoys are represented in this case study.

An evaluation of the wave spectrum shows again good agreement resolving the bi-modal seas as in case 2. All mean wave direction estimates resolve the low frequency swell from the south and higher frequency wind seas from the northwest. The directional spread shows agreement as seen in case 2 and 3. The significant wave height of all the buoys varies between 1.92 and 1.83 meters.

C. RESULTS

The intercomparison of the Datawell MK-II accelerometer buoy, Datawell DWR-G7 and DWR-G4 GPS buoys, and the off-the-shelf GPS prototype buoys present close agreement among all of them. In the energetic part of the wave spectrum, the buoys clearly resolved the sea state with distinct swell and sea peaks. However as we have seen in the previous chapter the prototype buoys with the MMCX receivers diverge from the Datawell buoys in the higher frequency tail (above 0.25 Hz). The higher spectral levels are indicative of an elevated noise level. Similar discrepancies were also noted in the comparison of MMCX and accelerometer sensors on the same buoy in Chapter IV indicating that the MMCX receiver reaches its intrinsic noise limitation. Wave energy levels are relatively low in this part of the wave spectrum and thus errors in estimates of the dominant wave properties are small. The intercomparisons show good agreement in the mean wave direction across all the case studies. The directional spread estimates agree in the dominant part of the spectrum, while the prototype buoys diverge at frequencies higher than 0.2 Hz with a positive bias, again indicating a noise level limitation of the MMCX receiver.

This study indicates that the prototype buoys with the Magellan MMCX system have the capability to accurately track wave excursions in the energetic part of the wave spectrum. For routine wave monitoring applications, inexpensive off-the-shelf GPS equipped buoys can provide wave energy and directional measurements equivalent to the considerably more expensive Datawell buoys.

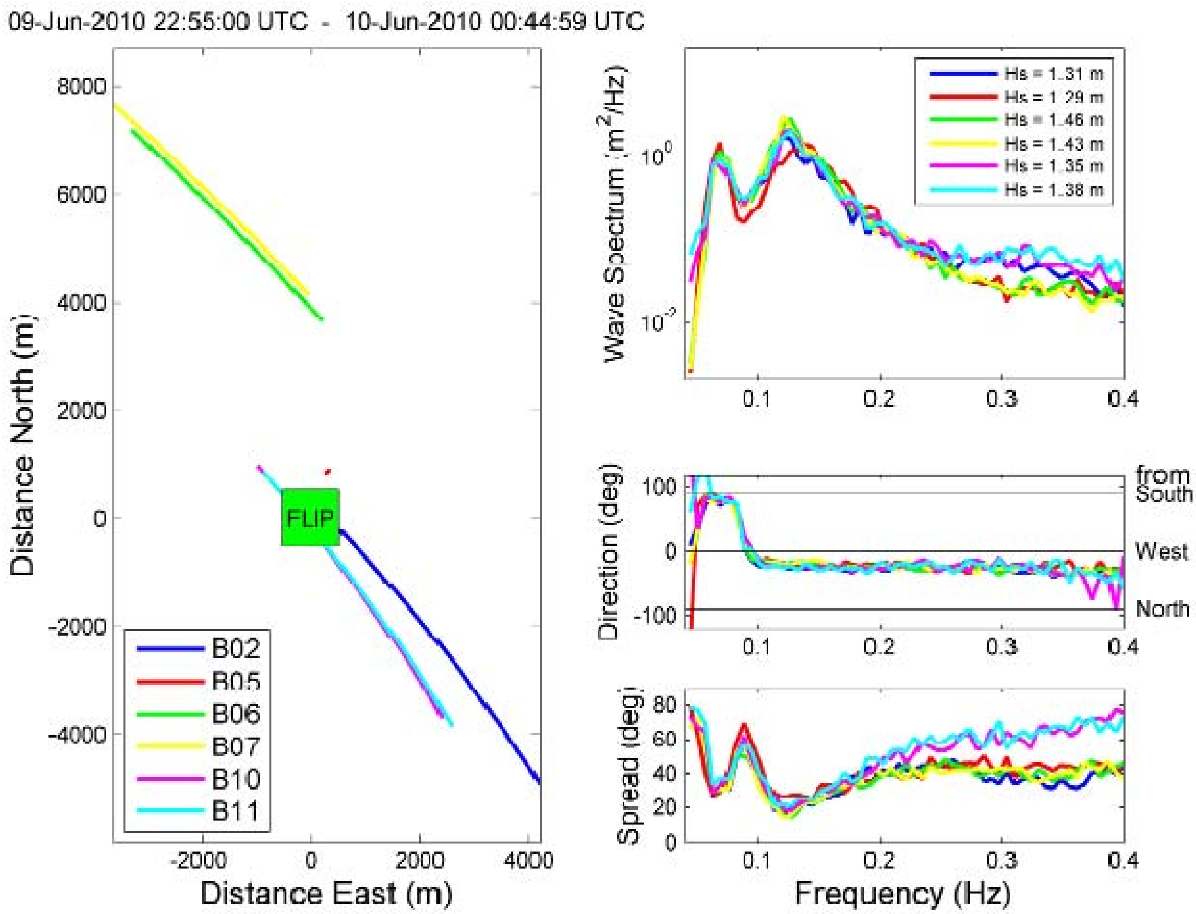

Figure 24. 09 June 2010, intercomparison between Datawell Waverider MK-II (B02), DWR-G7 (B05), DWR-G4 (B06, B07), Prototype buoy 1 (B10), and Prototype buoy 2 (B11). Left panel: buoy drift with reference to R/P FLIP. Right panels from top to bottom: wave energy spectra, mean direction spectra, and directional spreading spectra.

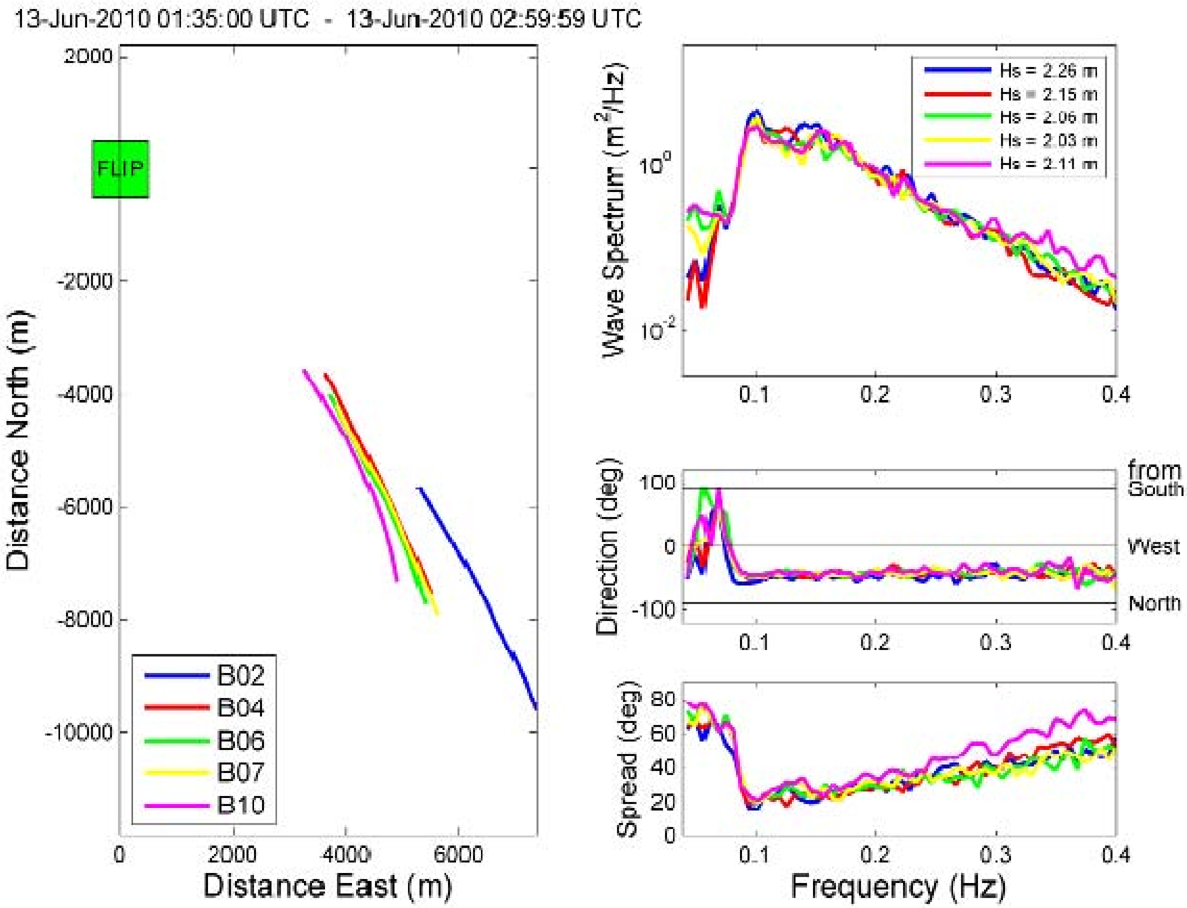

Figure 25. 13 June 2010, intercomparison between Datawell Waverider MK-II (B02), DWR-G7 (B04), DWR-G4 (B06, B07), and Prototype buoy 1 (B10). (same format as Figure 24)

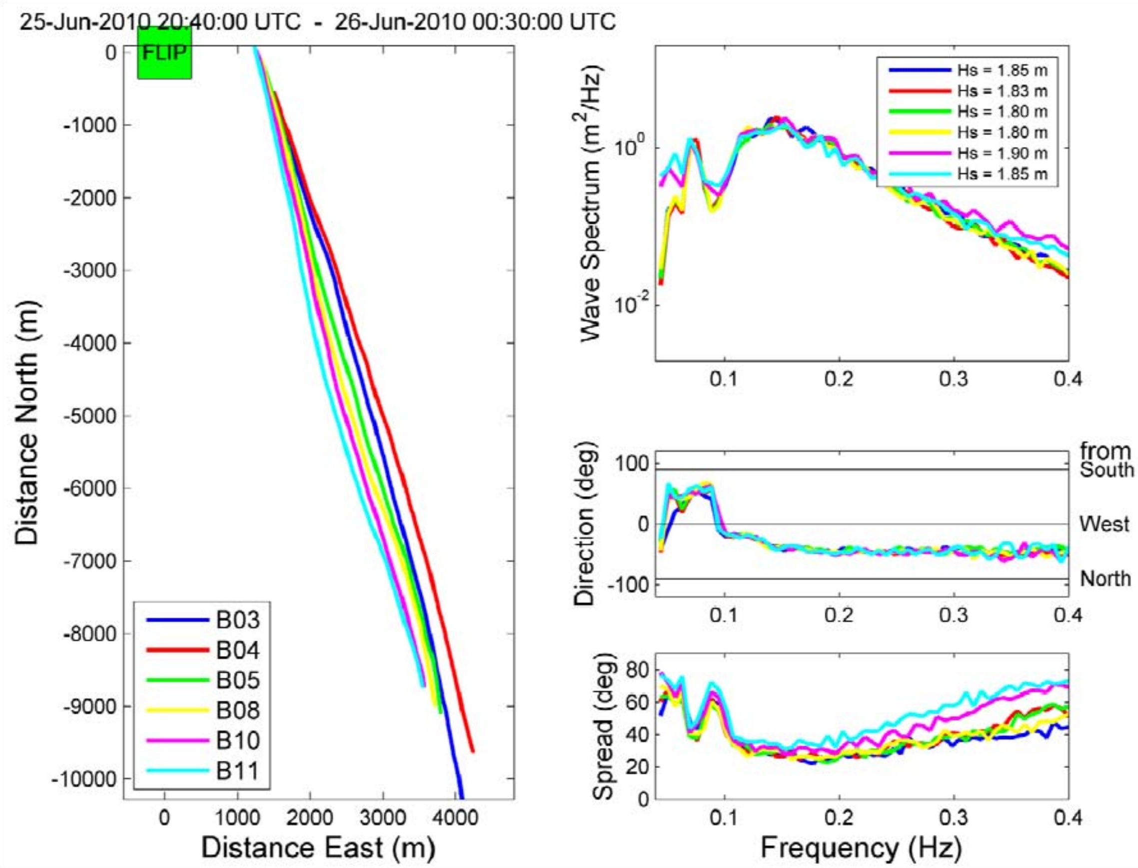

Figure 26. 25 June 2010, intercomparison between Datawell Waverider MK-II (B03), DWR-G7 (B04, B05), DWR-G4 (B08), Prototype buoy 1 (B10), and Prototype buoy 2 (B11). (same format as Figure 24)

VI. SUMMARY AND CONCLUSION

The main objective of this research was to determine the viability of using off-the-shelf GPS receivers to measure ocean surface waves. The field experiment was conducted off the California coast near Bodega Bay. We evaluated the performance of Datawell GPS-based Waverider buoys through intercomparison with the older, well-established Datawell accelerometer-based buoys, and we tested inexpensive prototype buoys equipped with a Magellan MMCX GPS system.

The first phase of the research was an intercomparison of wave measurements from the 0.9-m diameter Datawell Waverider's accelerometer sensor, with a Magellan MMCX GPS system and GlobalSat MR-350 GPS system mounted on the same Datawell MK-II 0.9-m buoy to assess the accuracy of the off-the-shelf GPS sensors. The second part of the project was an intercomparison between the Datawell accelerometer buoy, the Datawell GPS buoys, and the prototype GPS buoys built by the NPS team. Six case studies were reviewed for this study. For the sensor intercomparisons, three cases were selected to enable the widest range of sea condition possible. For the buoy intercomparison, three cases were selected that offered the widest array of deployed buoys as well as different wave conditions.

The intercomparison of the Datawell MK-II accelerometer sensor and the off-the-shelf GPS receivers yielded encouraging results. The Magellan MMCX system accurately tracked both vertical and horizontal wave orbital excursions. This GPS system had the closest agreement to the accelerometer sensor. At the dominant wave frequencies, the spectral levels, mean direction, and directional spreading estimates are in excellent agreement with the independent buoy accelerometer measurements. At high frequencies in the tail of the spectrum, a positive bias in spectral levels and directional spreading indicates a noise limitation, but the primary features of the wave field including multi-directional bi-modal sea states are well resolved. The GlobalSat MR-350 system accurately tracked horizontal wave excursions but showed a low bias in the vertical wave excursions. This is probably because the small bulkhead antenna that was mounted directly onto the Pelican case resulted in multi-path reflection. This error could possibly be reduced by placing a thin piece of reflective metal underneath the MR-350's antenna to inhibit multi-path reflection. Overall, both off-the-shelf GPS systems proved they could reliably provide routine wave information that can be extracted from either the horizontal or vertical displacement data.

The second phase of the project comparing all the buoys showed good agreement between the newer GPS buoys (both Datawell GPS Waveriders and the prototype off-the-shelf GPS buoys) and the traditional Datawell accelerometer buoys. The buoys clearly resolve the sea state, recognizing unmistakably distinct peaks in the energetic part of the wave spectrum. The prototype buoys were equipped with the MMCX receiver, that due to elevated noise level discrepancy limitation diverged from the Datawell buoys in the higher frequency levels where wave energy is relatively low. However, the intercomparison demonstrated good agreement in the mean wave direction and directional spread in the dominant part of the spectrum.

This study indicates the exceptional potential for use of inexpensive off-the-shelf GPS equipped buoys for use in measuring surface gravity waves. The prototype buoys used in this study have proven they can reliably track wave excursions in different sea states resolving wave spectra, mean wave direction, and directional spreading in the energetic part of the wave spectrum. Although much work remains to be done to refine the buoy construction and data acquisition system, advancing this technology will give forecasters the accurate and timely data of the sea state they operate in, enabling the naval command structure to make real time, effective decisions to complete their missions.

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